

Lecture 22: Hadron Collider Physics (I)

Nov 14, 2016

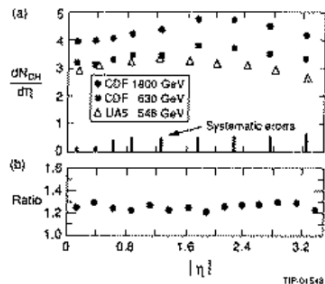
Why Hadron Colliders

- e^+e^- annihilation provides a clean environment
 - ▶ Center-of-mass energy known
 - ▶ All energy goes into creation of new particles
 - ▶ Coupling to all objects with charge with rates $\propto q^2$
- But electrons are light: large amount of radiation when they are accelerated
 - ▶ Difficult to make high energy colliders
 - ▶ Largest \sqrt{s} achieved at LEP: 209 GeV
- Hadron colliders can achieve much higher energy
 - ▶ Highest \sqrt{s} to date at LHC: 13 TeV
- In addition, hadron collisions provide direct access to gluons

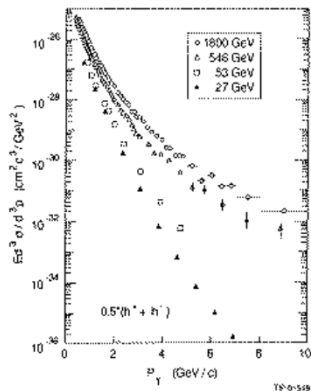
Phenomonology of Hadron Collisions

- Cross section dominated by soft processes
- Low momentum transfer \rightarrow cannot describe bulk of cross section using perturbative QCD
- As with fragmentation, use phenomenological models
- Qualitative features:
 - ▶ Limited p_T wrt beamline
 - ▶ Longitudinal momentum distribution dominated by phase space
- Expectations particle production in soft interactions same as what we saw in e^+e^- hadronization:
 - ▶ Multiplicity rises $\sim \ln(s)$
 - ▶ Particle production flat in rapidity (measured wrt beamline)
 - Since particle mass not measured, replace with angular variable
 - Pseudorapidity $\eta \equiv -\ln(\tan(\theta/2))$
Same expression you saw in hw # 5
 - ▶ Spectrum falls rapidly with p_T

Characterizing the soft physics: “Minimum Bias” events



- Particle production flat in η
- Small rise in $dN/d\eta$ with \sqrt{s}

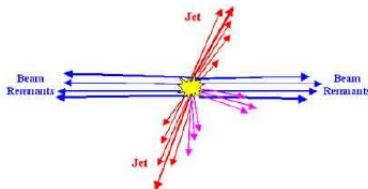


- dN/dp_T falls exponentially for low \sqrt{s}
- As \sqrt{s} increase, high tail develops

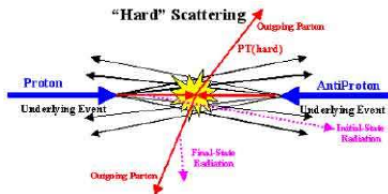
Onset of hard scattering!

Underlying Event and Hard Scattering

- Hard Collision leaves remnants of incoming p's moving in Beam Direction

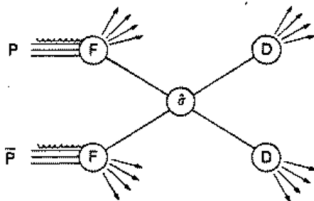


- “Initial State” gluon radiation largely co-linear with incoming partons: same basic structure



Soft particles distributed
uniformly in η

Calculating Hard Scattering Cross Sections



$$d\sigma(a+b \rightarrow c+d+X) = \sum_{ij} f_i^{(a)}(x_a) f_j^{(b)}(x_b) d\hat{\sigma}(i+j \rightarrow c+d+X') D_{c/C}(z_c) D_{d/D}(z_d)$$

- $\hat{\sigma}$ calculated using QCD
- $f(x)$, $D(z)$ measured in reference processes;
Exhibit scaling violations: $F(x, \mu)$, $D(z, \mu')$
- Note: example here is $2 \rightarrow 2$ scattering; $2 \rightarrow 1$ and $2 \rightarrow N$ also possible

Hard Scattering: General Observations

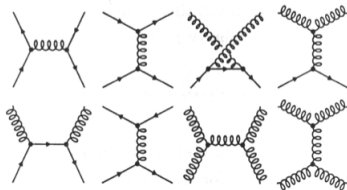
Two “beam jets” plus high p_T objects

- Hard Scattering
 - ▶ $\hat{s} = x_a x_b s$ where x 's are the fraction of the hadron momenta carried by the interacting partons
 - ▶ p_T in general is well measured
 - ▶ p_Z can be large. Usually not well measured directly (losses down the beampipe)
 - ▶ Cross sections for hard scattering can be calculated using perturbative QCD
- Beam Jets: “Underlying Event”
 - ▶ Limited p_T wrt beamline
 - ▶ Looks alot like soft events
 - ▶ Presence of hard scatter \longrightarrow larger $p\bar{p}$ overlap, so mean p_T and multiplicity somewhat higher

Examples of Hard Scattering Processes

- Elastic Scattering

$gg \rightarrow gg, gq \rightarrow gq, qq \rightarrow qq, \text{etc}$



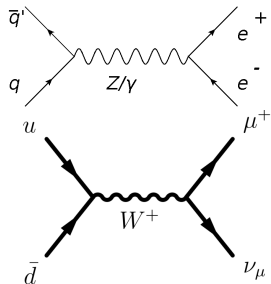
- Compton Scattering

$gq \rightarrow gq, gq \rightarrow g\gamma, \text{etc}$

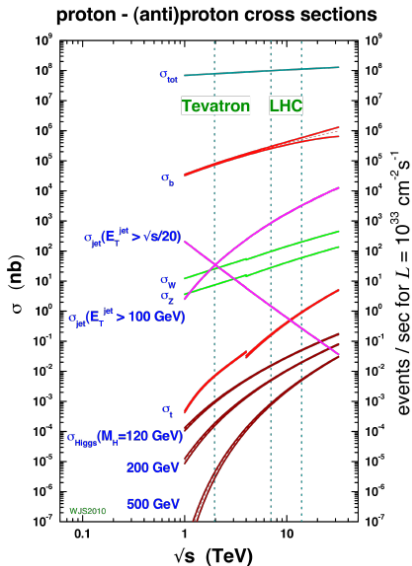


- Annihilation

$q\bar{q} \rightarrow qq, q\bar{q} \rightarrow \ell^+\ell^-, q\bar{q} \rightarrow W, q\bar{q} \rightarrow Z \text{ etc}$



Predicted Cross Sections

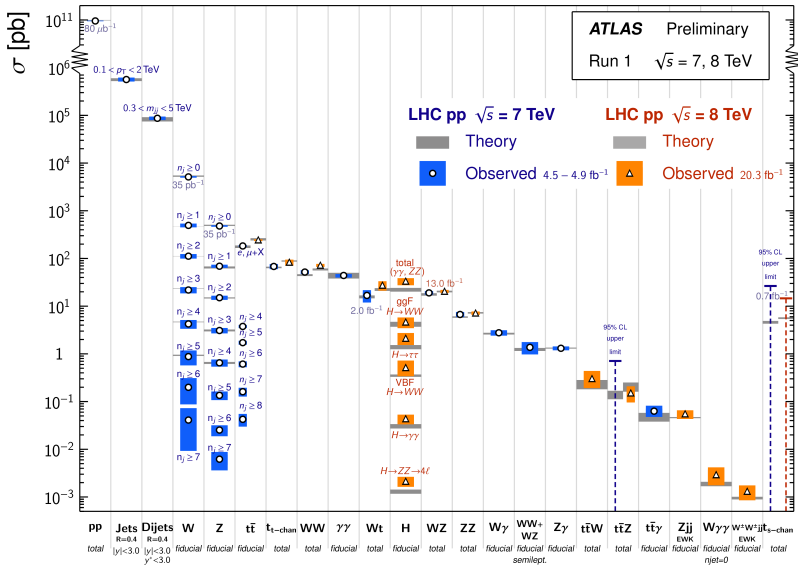


- Rates determined by
 - ▶ Hard Scattering Cross Section
 - ▶ Parton luminosity
- QCD processes dominate
 - ▶ EW rates lower by α/α_S
- For given s , cross sections decrease rapidly with \hat{s}
 - ▶ Heavy particles difficult to produce

How well do these calculations do?

Standard Model Production Cross Section Measurements

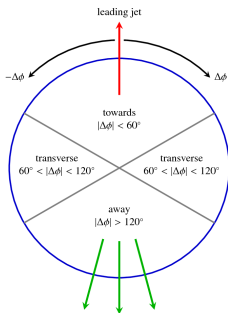
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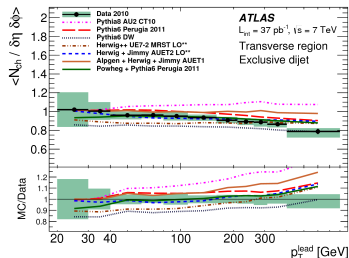
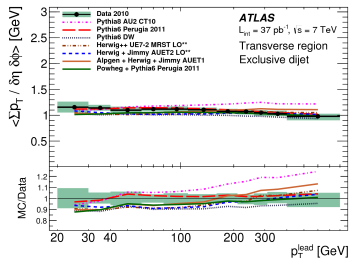
Analysis Strategy: Begin with the largest cross section and work down

- Characterize bulk of cross section “soft physics”
 - ▶ Tracks
- Identify dominant $2 \rightarrow 2$ QCD processes
 - ▶ Jets
- Develop strategies for selecting EW processes
 - ▶ e, μ, ν, γ
- Reconstruct heavy objects produced strongly
 - ▶ Top
- Understand discovery potential for low rate EW processes
 - ▶ Dibosons
 - ▶ Higgs
- Develop strategies to look for new physics (BSM)

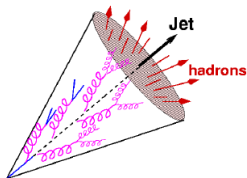
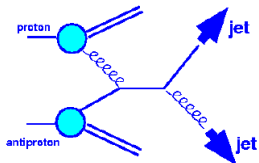
Track distributions from underlying event



- Look away from the hard scattering products (jets or leptons)
 - Eg, 90° from jets in a dijet event
- Particle multiplicity almost independent of jet p_T
- Remnants of the initial hadrons moving down beamline with limited p_T with respect to beam direction



QCD Jets



- Strategy:
 - ▶ Calorimeter based pattern recognition
 - ▶ Associate tracks with jets after calorimeter jets found

First Evidence for Jets in Hadron Colliders (UA2, 1982)

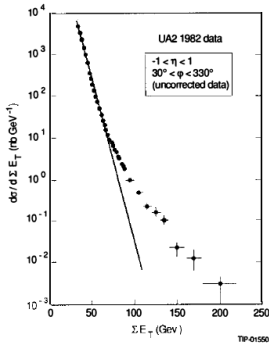


Figure 3 The observed distribution of $d\sigma/d\Sigma E_T$ as a function of ΣE_T , as measured by the UA2 experiment. The solid line shows the exponential falloff at low ΣE_T .

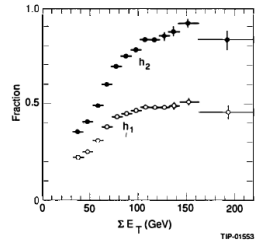


Figure 4 The fraction of the total transverse energy observed in the highest (h_1) and two highest (h_2) clusters as a function of the total transverse energy of the event, as measured by the UA2 experiment.

$p\bar{p}$ interactions at 546 GeV ($S\bar{p}pS$ collider at CERN)

- High tail in ΣE_T indicates onset of hard scattering
- Use simple nearest-neighbor clustering algorithm
- Majority of transverse energy in two clusters, back-to-back in ϕ
- Dijet system boosted in z : two initial partons carry different fractions of initial hadron energies

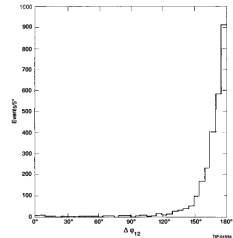
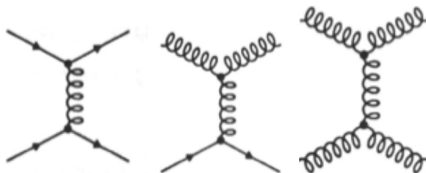


Figure 5 The distribution of the difference in azimuth between the two highest E_T clusters in events with $\Sigma E_T \geq 60$ GeV, as measured by the UA2 experiment.

Evidence for the non-abelian nature of the gluon

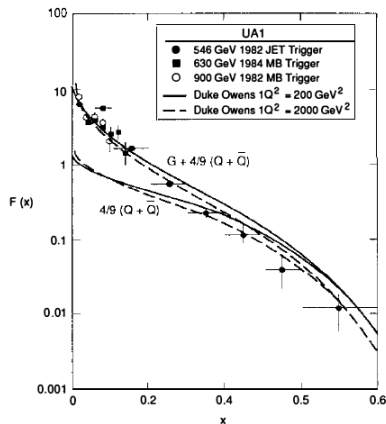


- Elastic parton-parton scattering
- t -channel exchange of a gluon
- All 3 processes have similar Feynman diagrams

- ▶ Different quark and gluon n color charge
- ▶ Different quark and gluon PDFs
- ▶ Define an “single effective subprocess” PDF

$$F(x) = G(x) + \frac{4}{9} (Q(x) + \bar{Q}(x))$$

- Clear evidence for gluon scattering



Angular Distribution

- t -channel pole leads to angular distribution

$$\frac{d\sigma}{d\cos\theta^*} = \alpha_s^2 \hat{s} \frac{1}{1 - \cos^2\theta^*}$$

- Rutherford-like shape with divergence in beam direction
- Change variables

$$\chi \equiv \frac{1 + \cos\theta^*}{1 - \cos\theta^*}$$

Distribution is approximately constant for $\chi > 2$

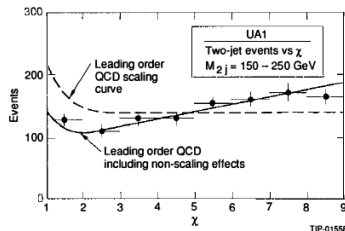
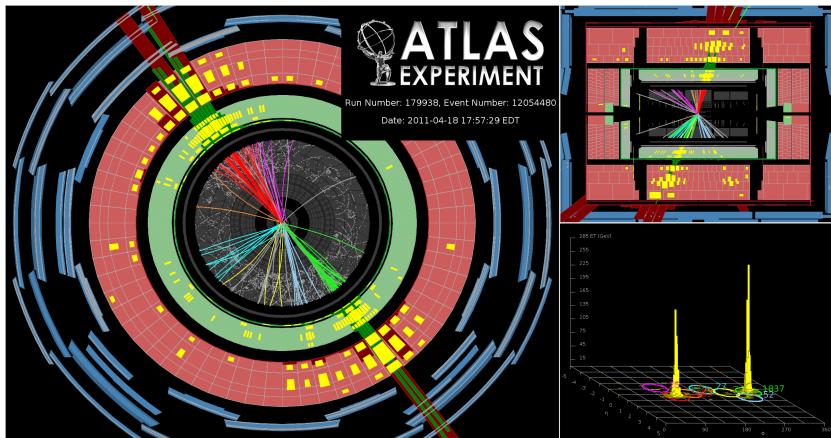


Figure 9 The distribution of χ for two-jet events as measured by the UA1 collaboration. The curve shows the predictions of a lowest-order two-parton scattering QCD calculation, with and without contributions due to QCD scaling violations.

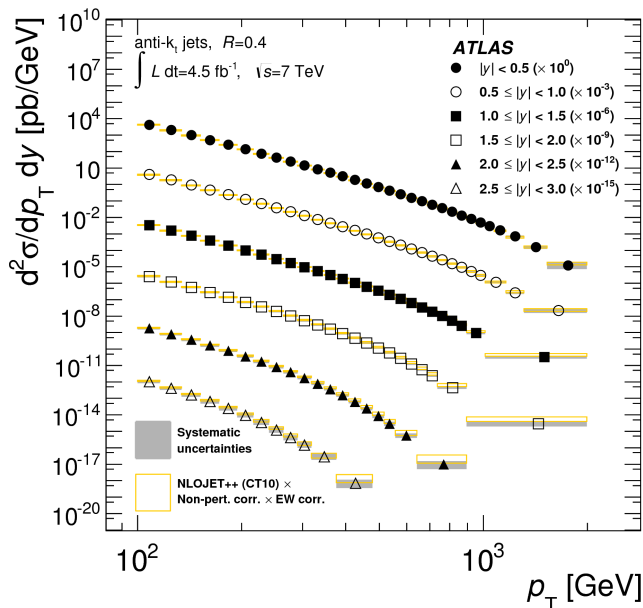
What do jets look like at the LHC?



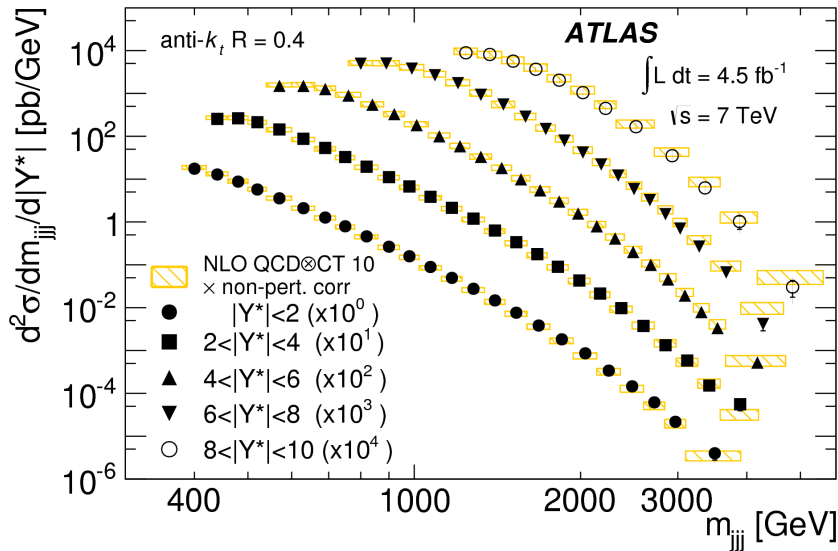
State of the Art: Theory and Experiment

- Hard scattering cross section at NLO or multileg (your choice)
 - ▶ Estimate uncertainties by evaluating dependence of calculation on choice of scale
- Well measured PDFs
- Jet finding algorithms that are infra-red and colinear safe
- Evaluation of non-perturbative effects through the use of Monte Carlo generators
 - ▶ Independent generators and generator tunes to assess systematic uncertainties
- Careful in-situ calibration of jet energy
- Corrections for pileup (multiple collisions in one beam crossing)

Can the theorists predict the cross section?



How about 3 jets?



Using dijet angular distribution to look for new physics

- Look for new resonance that decays to jets
 - ▶ Signal is a peak in dijet invariant mass
- In addition, new heavy resonance would decay with spherical angular distribution
 - ▶ Can distinguish from QCD background, which is peaked at large $\cos \theta^*$
 - ▶ Bin in dijet mass and plot χ
 - ▶ Signal would manifest as peak in low χ region
- Analysis requires good understanding of QCD background

